CHIN. PHYS. LETT. Vol. 30, No. 4 (2013) 046102

High Quality Pseudomorphic $In_{0.24}$ GaAs/GaAs Multi-Quantum-Well and Large-Area Transmission Electro-Absorption Modulators *

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(Received 21 November 2012)

The good quality of 200 pairs of highly strained $In_{0.24}$GaAs/GaAs multi-quantum-well (MQW) structure is demonstrated by the x-ray diffraction and photoluminescence curves. Large-area modulators based on the pseudomorphic $In_{0.24}$GaAs/GaAs MQW are designed and fabricated successfully, where the diameters are not less than 3 mm and the working wavelength is extended to 1064 nm. The single pass modulation depth is demonstrated to be 0.34 at 1064 nm at a reverse voltage of 80 V .

PACS: 61.05.cp, 78.55.Cr, 85.35.Be, 42.79.Hp DOI: 10.1088/0256-307X/30/4/046102

Large-area optical modulators have been explored recently for free-space communication.[1,2] A kind of asymmetric optical links is popular because compared with radio-frequency links, the optical terminals are smaller in size and the optical links are difficult to intercept. In such communication links, a modulator is used in conjunction with an optical retro-reflecting system, so that a remote laser directed at the system passes through the modulator, being imprinted with a data signal, and returns to the remote station, allowing readout of the data.[3] Some laboratories have worked on the development of modulator retro-reflecting (MRR) systems based on multiple-quantum-well (MQW) modulators.[1,3] This kind of transmission modulator is easier to grow and fabricate than the resonant-cavity enhanced modulator.[4]

Since reverse biases of tens of volts are typically required to drive the MQW modulator devices, a leakage of even 1 mA results in power dissipation in tens of milliwatt. InP-based 1.06 μm and 1.55 μm devices suffer lowered yield, due to the large leakage current under reverse bias. It will be a great problem since these devices are intended to operate in power limited situations. The dark current of GaAs-based modulators is quite low, but the working wavelength is limited to be less than 950 nm without InGaAs buffer layers.[5,6] They will act as a more important role if the longer wavelength can be reached.

In this study, the GaAs-based pseudomorphic $In_{0.24}$GaAs/GaAs MQWs is grown successfully as the active layer in an optical electro-absorption (EA) modulator. A thick barrier layer releases the strain of the high indium content InGaAs layer to acquire the high quality MQW structure. Thus this kind of device extends the working wavelength to 1.06 μm. The devices of large-area and low dark current density are demonstrated because of the GaAs-based high bandgap material and good crystal quality.

The modulator, consisting of 200 periods of $In_{0.24}$GaAs/GaAs QWs, was grown with a GEN Ⅱ MBE system on an n-type GaAs wafer, and was capped by a 120-nm p-type contact layer, thus forming a p–i–n diode. This device is a transmissive modulator designed to work at wavelength of 1.06 μm, compatible with high power laser sources. The well thickness is designed to be 8 nm to have efficient stark effect. Once grown, the wafer would be fabricated into discrete devices using a multi-step photolithography process consisting of etching, passivation, chemical mechanical polishing and metallization steps. The Ti/Au and Au/Ge/Ni were thermally deposited as the p and n contact. The experimental devices have a 3 mm aperture. The device diagram is shown in Fig. 1.

For the MQW optical modulator, the bandgap of the well is critical because of the application of quantum confined Stark effect. The bandgap is discriminated by the QW photoluminescence (PL), the mapping of which was measured at room temperature in the JY HR800 system, with the Ar-ion pump laser of 488 nm and an InGaAs detector cooled by liquid nitrogen. In Fig. 2, the result shows that the peak of the PL in the center part is about 1048.5 nm, which is the optimized result of indium content tuning of the InGaAs well layer. The full width at half maxi-

*Supported by the National Natural Science Foundation of China under Grant Nos 61274069, 61176053 and 61021003, the National High-Technology Research and Development Program of China under Grant No 2012AA012202, and the National Basic Research Program of China under Grant Nos 2012CB933503 and 2013CB932904.

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mum (FWHM) of the PL peak at room temperature is about 11.8 nm, 16 meV, which indicates the good crystal quality and favorable interface between the well and barrier layer. Except for the very marginal part of the wafer, there are little differences in the peak intensity and the FWHM. The uniformity of the epi-wafer is very helpful for the high yield of the large-area devices.

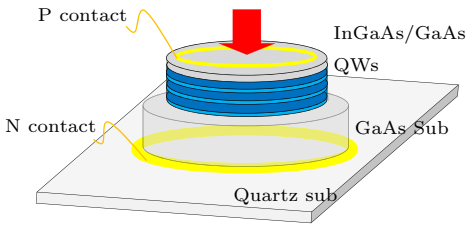

Fig. 1. MQW transmission optical modulator's device structural diagram.

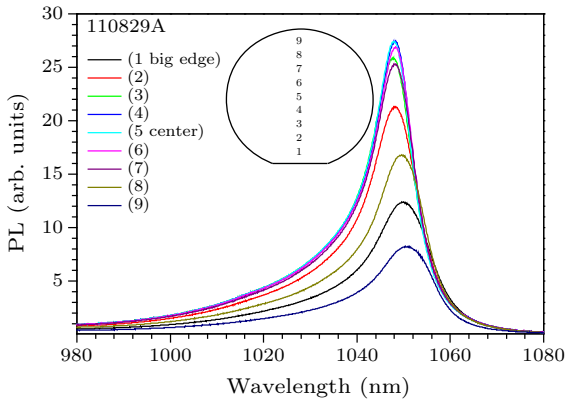

Fig. 2. PL spectra of the MQW transmission modulator at room temperature. The lines with different colors are in different test points on wafer. The peak is around 1048.5 nm and the FWHM is 11.8 nm except for the very marginal points of 1 and 9.

The epitaxial crystal structures were characterized using high-resolution x-ray diffraction with (004) Bragg reflection and Cu K_1 radiation. Figure 3 shows the x-ray rocking curve for the structure with a large number of satellite peaks, indicating the high quality of the grown material.[7] The estimated period of the MQW structure, using the angular separation of the satellite peaks, is about 58.7 nm, the InGaAs is estimated to be about 8.4 nm, which are in good agreement with the designed values of 58 nm and 8 nm. Because of the high-quality interfaces, the interference patterns could be observed clearly. With an average lattice mismatch of 3.25% derived from the simulation, the estimated indium composition in the quantum well is of 24%, under the condition that the layer is assumed to be coherently strained. The estimated value is in good agreement with the designed value. The $In_{0.24}GaAs$ layer of 8.4 nm is very close to the critical thickness on GaAs, which is about 10 nm.[7] When a thick GaAs layer is grown on this layer, we can find that the strain energy is mostly released and there are no obvious signs of strain accumulation and crystal relaxation of the 200 pairs of InGaAs/GaAs MQW structures.

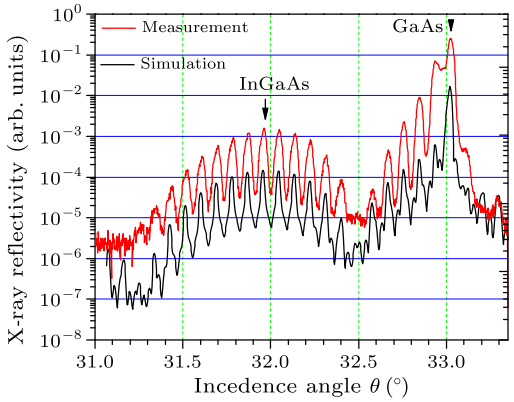

Fig. 3. The x-ray rocking curve of the 200 pairs of 8 nm/50 nm InGaAs/GaAs MQW structure. The red curve is the measurement result and the black one is the simulation.

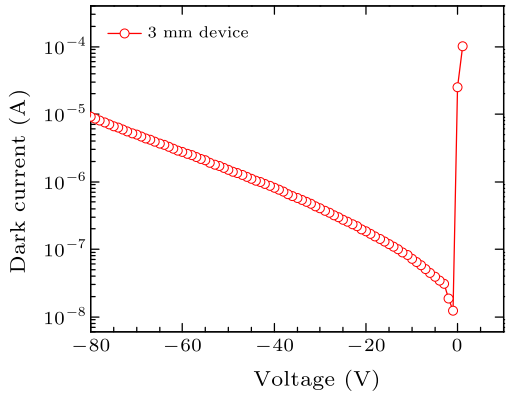

Fig. 4. The dark I–V curve of the 3-mm modulator device. The dark current is about -10^{-5} A under -80 V voltage.

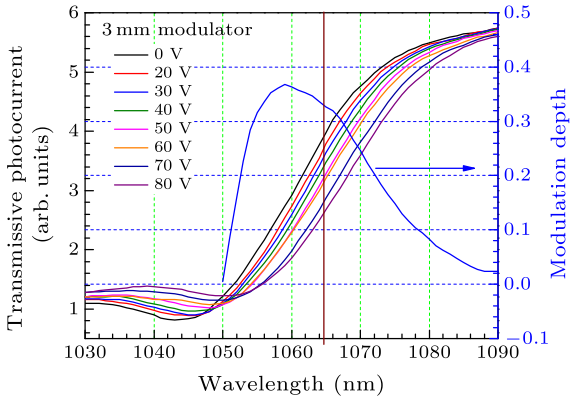

Fig. 5. The transmissive spectra of the 3-mm modulator. The modulation depth is about 0.34 at 1064 nm under 80 V negative bias voltage.

The high quality of the MQW can also be described from the I–V curve of the device with 3 mm diameter, as shown in Fig. 4. There should be no large

misfit dislocations in the epi-layer, respecting the low dark current density of 10^{-12} A/μm^2 in the electrical field of 70 kV/cm.

The modulation of the device is characterized by the transmission spectrum. As shown in Fig. 5, the transmission spectra of a modulator of 3-mm diameter under different bias voltages are presented. The single-pass modulation depth under 80 V is of 0.36 at 1060 nm and of 0.34 at 1064 nm, where the insertion loss is about 2.5 dB without AR coating. The devices with even larger diameters of 5 mm and 7 mm have the similar results, with no significant degeneration. The capacity of the device is 75 pF, and the estimated maximum modulation frequency is 40 MHz. Although the operation voltage is still high, it can be decreased by the cascade p–i–n structure.

In summary, the EA modulators with 200 pairs of highly strained 8 nm/50 nm $In_{0.24}GaAs/GaAs$ MQW have been demonstrated. There is no destructive accumulation of the strain and thus there are no obvious relaxation and collapse, which can be concluded from the results of x-ray diffraction and the PL spectra. The devices show a good choice of large-area low-dark-current modulators beside the InP-based QW structures in the 1.06 μm wavelength range.

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